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NOTE: This Progress Report is the basis for a proposed publication in Fire Technology. It has been carefully reviewed for technical accuracy by subject matter authorities. However, we anticipate the final published paper will receive substantial editorial changes in format and organization.

Pacific Southwest Forest and Range Experiment Station
Forest Service
U. S. Department of Agriculture
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BUILDING FIRELINES--HOW FAST DO CREWS WORK?

by

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ABSTRACT

Rates of production of firelines by organized handline crews were evaluated from a series of 56 fireline worklogs collected in California fires during the 1966-1968 fire seasons. Results of the data analysis express productivity rates in square yards per man hour. The rates have been computed from the sets of observations for periods of up to 10 hours of line time. Mean rates and variances of the rates are used to express, in a probabilistic form using the gamma distribution, the chance of completing at least a fixed rate of productivity over a specified period of time.

Key Words: Line construction, work rates, fireline production, hand-tool crews, probability.

Despite improvements in firefighting techniques and equipment, the organized hand-tool crew is still a major element of the suppression force of wildland fires. To allocate enough men for the job, the fire boss must know, or be able to estimate, how much fireline a man can build under various conditions of fuel, terrain, weather, and rate of fire spread. Sending a crew to a fire without knowing what it can accomplish over a period of time can lead to wasted time and effort--or perhaps a catastrophe.

In California, published guidelines for estimating crew productivity are based on tests in different fuel types under non-fire conditions. Experience has shown, however, that crews under stress on actual fires do not build lines as

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fast as the basic published rates of fireline construction. A recent preliminary test of crews in light fuels suggested, for example, that the actual rate was about one-third of the published rate; in heavier fuels, however, the two rates were reasonably close.[1/] Because of uncertainty about how closely the guides could be applied in actual fire, a more detailed study was begun. In the study, data were drawn from actual fires, productivity rates were computed in area and linear units, and rates of productivity were expressed in probability form. By using the method described in this report, the fire boss can estimate the rate of line construction by large hand-tool crews in different fuels.

EARLIER STUDIES

In 1937 and 1938, studies were made in the U. S. Forest Service's California Region to determine how fuel types differed in resistance to control.[2/3/] The 1937 study used an experienced three-man crew, working a maximum of four 45-minute periods in a given day under non-fire conditions; lines were cut in level terrain to a standard width. In the 1938 field tests, variable-sized crews cut standard widths for one hour; over 200 observations were made in about 35 fuel conditions.

In 1940, the line construction rates derived in these resistance-to-control studies were published in the Forest Service Fire Control Handbook[4/] as a guide to estimating productivity of fire crews. Rates were expressed in terms of chains per man hour. These rates have remained unchanged since 1940, although an alignment chart was added to the Fireline Notebook in 1963.[5/]

To account for loss in crew productivity over time, the rates were adjusted down 25 per cent per hour, a 10 per cent loss due to fatigue and a 15 per cent loss due to a required 10-minute break each hour ($\frac{10 \text{ min.}}{60 \text{ min.}}$ = about 15 per cent). McMasters[6/] later expressed this loss of crew productivity in an equation:

$$R(T) = 0.833\ K(0.9^{t-1}) \qquad (1)$$

in which

$R(T)$ = chains per man per hour during the t^{th} hour

K = basic rate of chains per man per hour

.833 = a factor which expressed 50 minutes of work per hour

0.9 = efficiency of men after an hour's work

COLLECTING DATA

Field data for the study, reported in this paper, were collected in California during the 1966-1968 fire seasons--primarily by employees of the California Division of Forestry who recorded the progress of suppression crews. Crews ranged in size from 5 to 29 men, and averaged 14.9, with standard deviation of 3.87 men per crew. Most of them were highly-organized crews from the U. S. Forest Service or the California Department of Corrections.

In 1966, work periods were recorded on the basis of a change of fuels, terrain, fire behavior, or other factors. This method resulted in recording periods ranging from 3 to 120 minutes. In 1967 and 1968, completed handline was measured at regular 15-minute intervals--a more reliable recording procedure. Work breaks, changes in fuel-type or slope, and other items of this type were recorded as they occurred. This format resulted in a cumulative record of fuel types encountered, length and width of fireline, and time spent in construction.

Some of the records of crew performance in 1966 and 1967 had to be discarded because of obvious errors or omissions. Of the 32 individual crew records collected in 1966, 11 were excluded from the study. Of the 15 records collected in 1967, 3 were excluded.

Actual work time spent on fires--not total time spent on the line--ranged from 20 to 485 minutes. Frequency of fires of varying lengths of total line time were as follows:

Total Time (Minutes)	Number of Fires
0-60	8
61-120	16
121-180	5
181-240	3
241-300	5
301-360	3
>360	16

Of the 17 fuel types coded in the Forest Service Fire Control Handbook,[5/] crews encountered all but types 3, 4, 10, and 16. In this study, the 17 fuel types were divided into four groups; the fuel types within each group required about the same amount of time for line construction. The four groups were: I (light fuels, such as grass); II (medium brush, such as light to medium chamise); III (heavy brush, such as medium oak); and IV (heaviest brush, such as dense chamise). Crews almost always encountered more than one fuel type--especially when they worked longer than an hour on a fire.

COMPUTATION OF CONSTRUCTION RATES

A computer program was developed to calculate work rates for individual crew records -- cumulative and periodic rates of square yards per man per hour, and cumulative rate of chains per man per hour. Work rates were based on total line time, and include breaks and other non-productive activities.

Area was deemed easier to use than chains in computing work rates for this study. And it provides a standard of measure for the various fuel types by including both length and width. Length of fireline constructed multiplied by average of first and last width measurements, gives the number of square feet completed during the period. Hourly work rates are computed for each time period from the equation:

$$S = \frac{\text{area} \times 60.0}{N \times 9.0 \times Z} \qquad (2)$$

in which Area = number of square feet completed

S = square yards per man per hour

N = number of men in the crew

Z = length of period in minutes

The cumulative rate of line construction, at a given time, is considered to be a more useful measure of crew productivity than the rate for any 15-minute period. The cumulative rate is the number of square yards per man hour for the period of time since the start of the fireline record. It is derived from the total elapsed time and total area of completed fireline:

$$S = \frac{\text{area} \times 60.0}{N \times 9.0 \times X} \quad (3)$$

in which Area = number of square feet completed

S = square yards per man per hour

X = total elapsed time (minutes) since start of record

N = number of men in the crew

The cumulative value of chains per man per hour was also computed. This computation does not consider the measured line widths. It was derived for each time in this form:

$$Ch = \frac{Tf \times 60.0}{N \times 66.0 \times X} \quad (4)$$

in which

Ch = chains per man per hour

Tf = total lineal feet of line built in time X

X = total elapsed time (minutes)

DATA ANALYSIS AND RESULTS

Productive work time versus total time on the fireline is important in estimating how much line may be constructed in a given period of time (Figure 1). The regression equation of work time to total time on the line is:

$$WT = 2.2160\ TT.^{.79572} \quad (5)$$

in which

WT = work time in minutes

TT = total time in minutes

Figure 1. Relation of productive work time in fireline construction to total time spent on the fireline.

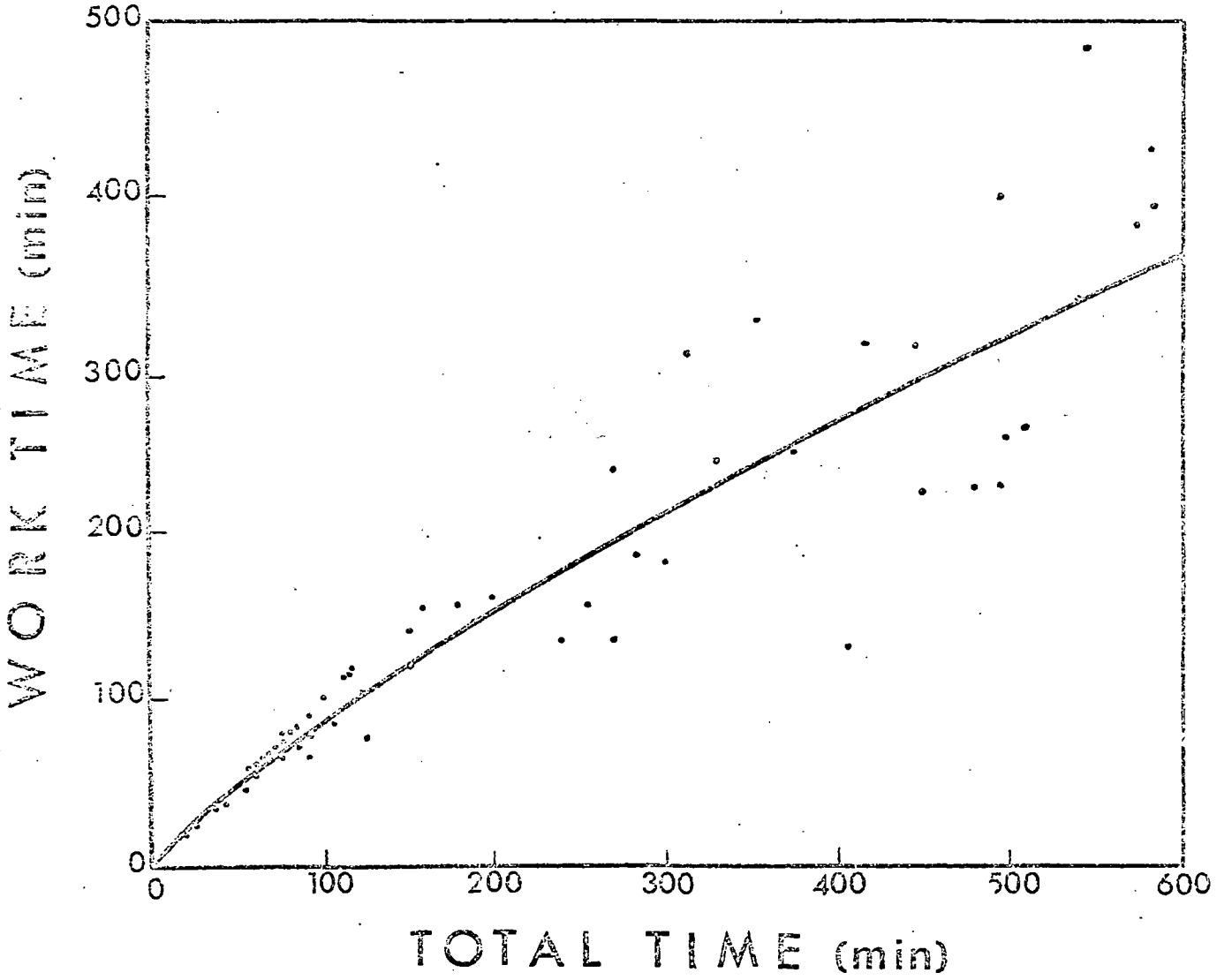

WORK TIME (min)
500
400
300
200
100
0
0
100
200
300
400
500
600
TOTAL TIME (min)

TABLE 1. Cumulative rates of fireline construction in units of square yards per man per hour of total time on fireline; rates and variances for each of four (4) resistance to control groups[1] and for all groups combined.

Min.	All Groups			I			II			III			IV		
	No. obs.	Mean rate (sq. yds.)	Variance	No. obs.	Mean rate (sq. yds.)	Variance	No. obs.	Mean rate (sq. yds.)	Variance	No. obs.	Mean rate (sq. yds.)	Variance	No. obs.	Mean rate (sq. yds.)	Variance
30	54	20.26	168.7	15	20.45	143.5	16	20.82	136.5	18	22.08	256.1	5	11.33	17.2*
60	52	19.14	137.0	13	21.66	265.2	17	21.64	95.1	15	17.26	115.2	7	12.38	18.2*
120	32	16.99	113.9	8	18.36	161.3	10	20.56	171.1	9	13.53	50.3	5	13.91	40.18
180	28	15.96	84.7	6	12.12	19.5	8	23.07*	167.5	9	13.00	26.4*	5	14.50	55.8
240	25	14.50	54.4	4	16.61	28.7	8	18.71	89.8	8	10.79	21.5	5	12.00	35.0
300	20	13.31	50.7	2	14.10	2.4	7	17.83	79.5	7	9.95	16.9	4	10.92	45.6
360	16	13.58	61.7	1	11.77	-	7	17.22	99.5	5	12.66	15.7	3	7.23	22.9
420	13	12.86	69.9	1	10.99	-	6	17.12	120.9	4	9.07	5.3*	2	8.60	11.9
480	11	10.11	11.8	1	10.59	-	5	12.29	14.5	3	8.03	1.1	2	7.57	8.3
540	6	10.52	11.4	0	-	-	4	11.72	13.2	1	8.04	-	1	8.17	-
600	1	7.47	-	0	-	-	1	7.47	-	0	-	-	0	-	-

[1] Group I (light fuels, such as grass); II (medium brush, such as light to medium chamise); III (heavy brush, such as medium oak); IV (heaviest brush, such as dense chamise).

*Statistically significant at 10 per cent level.

Up to about 40 minutes, this equation overestimates work time; that is, work times are slightly larger than total times. But if the total time is up to 60 minutes, the ratio is nearly 1:1 -- work and total times are nearly equal. As total time increased, time for rests and other nonproductive activity increased. The ratio of work time to total time was 0.85:1 at 100 minutes, and about 0.60:1 by 600 minutes.

Average cumulative work rates in square yards did not decrease much over the 10-hour period -- at five hours the average rates were approximately 65 per cent of the rate at 30 minutes (Table 1). Average line construction rates over sixty 10-minute intervals had a nearly linear trend.

The variance in work rates dropped rapidly during the first hour, then leveled off but continued to drop slowly. Three factors help explain this reduction in variance: one is the crew's initial reaction to the fire. In the first 60 minutes, crews will perhaps work extremely hard if they feel that the fire can be quickly controlled. But they may tend to pace themselves more conservatively if the fire appears to be of longer duration. A second factor is use of the cumulative rates. Fluctuations of periodic rates have a progressively smaller effect on the cumulative rate. After several hours, a change in fuel type or line width, which may drastically change the periodic rates, will not cause an appreciable change in cumulative rates. And a third factor -- fire behavior and the crew's condition, experience, and leadership -- may also be responsible for variations in the rate of line construction.

To determine if the mean cutting rates for each of the fuel groups differed from the average of the total group, I tested for homogeneity of variance with the F-test. Four hourly fuel group variances were significantly different from the total group variance (Table 1). An assumption of uniformity of variance led to the next step, a t-test of the hourly mean rates. The hypothesis tested was that each fuel group mean was equal to the corresponding hour total group mean. Results of this test indicated one fuel group mean (Group II at 3 hours) was significantly different from the total average. It was reasonable to assume that area work rates were nearly the same in each of the four fuel groups. This assumption permitted consideration of the hourly work rates to be made in terms of the total group averages and variances. Trends of the means and variance rates over 600 minutes can be shown by linear regressions based on these variables at sixty 10-minute periods. The best least square regression of the mean variables is:

$$\hat{Y} = 32.634 - 7.6979 \ (\text{Log}_{10}\text{Time}) \qquad (6)$$

in which

$\hat{Y}$ = square yards per man per hour

Time = minutes of total time on line.

r = correlation coefficient = -.9456

Regression of the variance is:

$$\text{Var}\ (Y) = 489.664 - 174.679\ \text{Log}_{10}\text{Time} \qquad (7)$$

in which

Var (Y) = variance of mean rate

Time = minutes of total time on the line.

r = correlation coefficient = -.9212

Equations 6 and 7 were used to establish estimates of the probability of constructing line at specified hourly rates. For example, at the end of two hours what is the probability that a crew will have constructed 20 square yards per man per hour? Estimating this probability is possible from computations of the cumulative gamma distribution.[7] Values used for solution of the gamma distribution are derived from the estimate from equations 6 and 7. Probability estimates are shown in Figure 2 and Table 2.

Fuel types require different widths of line to be an adequate fire stop. The Fireline Notebook[5] reports values of normal width for these California fuels. Averages of these normal widths for the four fuel groups and averages of the actual width measurements are:

Fuel Group:	Handbook Normal Width (ft.)	Actual Measured Width (ft.)
I (light fuels)	2.5	3.6
II (medium brush)	3.5	5.7
III(heavy brush)	5.0	5.4
IV (heaviest brush)	6.0	5.8

Average measured widths show that in Groups I and II (light fuels) crews cut lines wider than the width termed normal. To convert area rates into a linear measure (chains), line widths required to stop the fire need to be selected. This width depends on slope, wind, temperatures, and other environmental factors as well as fuel type. A direct conversion of area rates, by various line widths, into chains per man per hour, is easily made from Figure 3.

Figure 2. Probability (per cent) of achieving a given rate of productivity (square yards/man/hour) for 1, 3, and 5 hours of time on fireline.

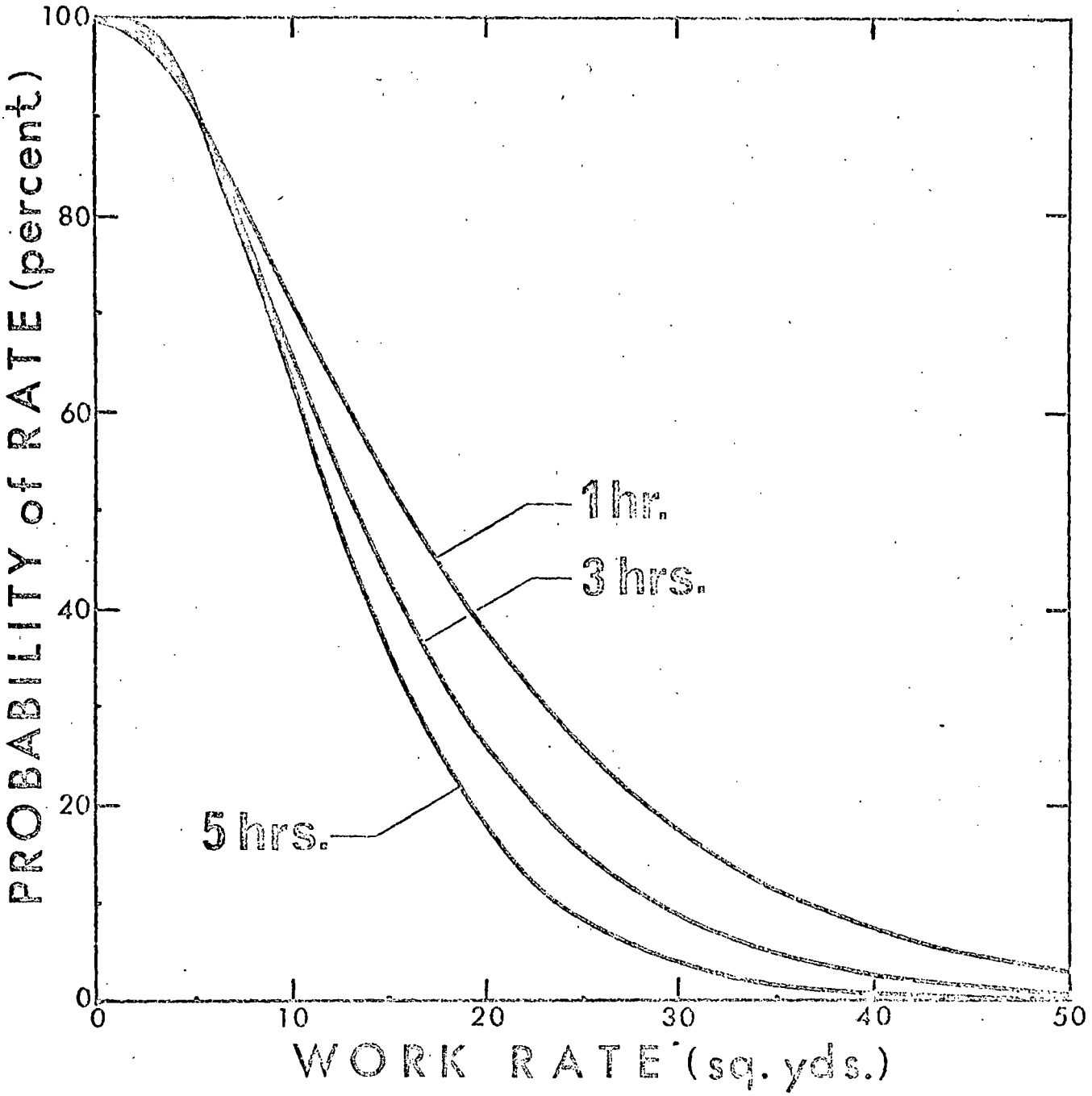
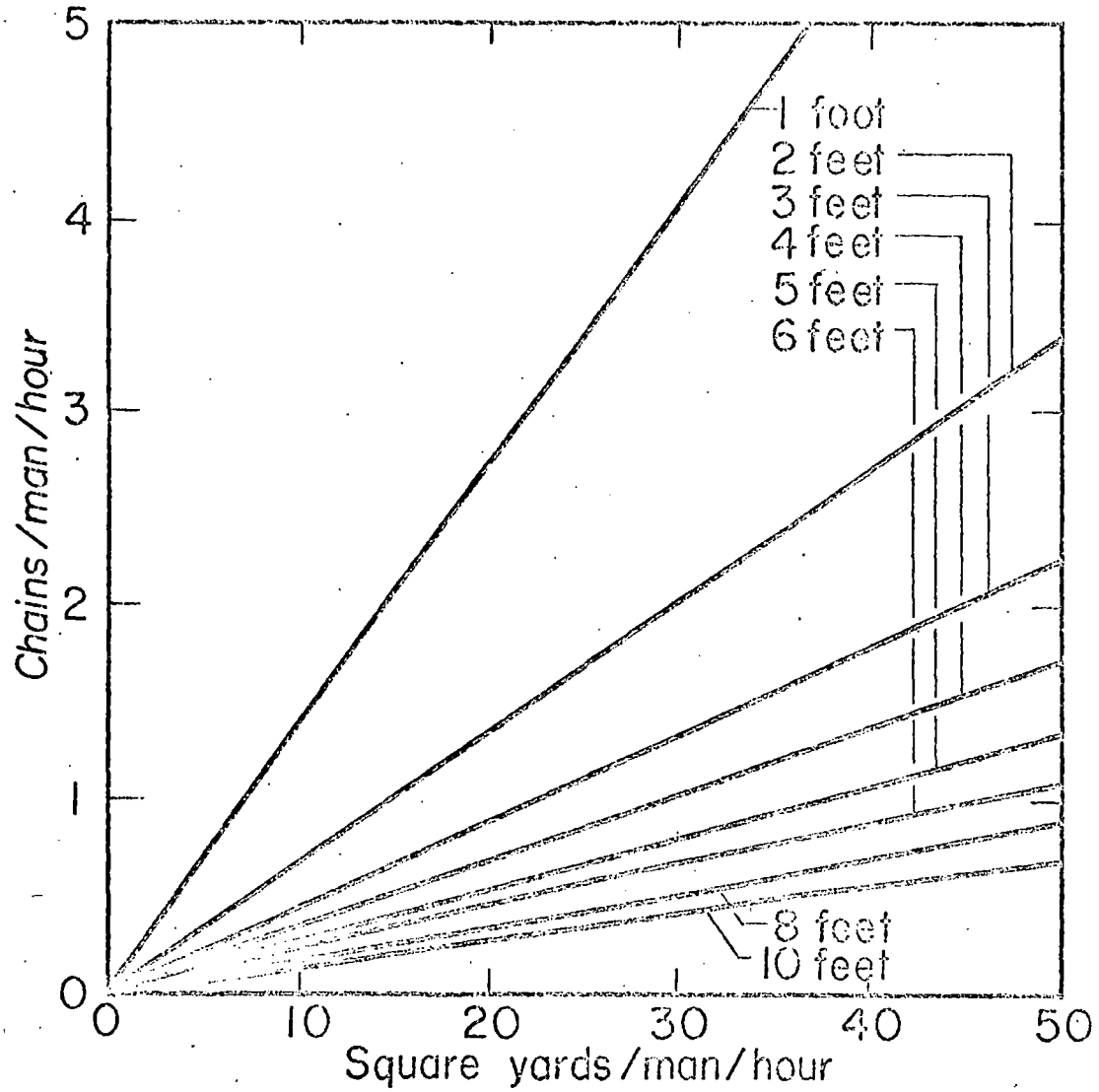

PROBABILITY of RATE (percent)
100
80
60
40
20
0
0
10
20
30
40
50
WORK RATE (sq. yds.)
1 hr.
3 hrs.
5 hrs.

TABLE 2. Probability (per cent) of attaining a fixed rate of fireline productivity for given periods of work time.

Cutting Rate (sq. yds./man/hr.)	Hours							
	1	2	3	4	5	6	7	8
	Percent							
5	90.0	89.0	89.0	89.4	90.5	91.9	93.7	95.9
10	71.5	67.6	65.4	63.9	62.9	62.3	62.3	62.8
15	53.1	49.9	42.7	39.3	35.8	32.33	29.1	24.3
20	37.7	30.7	25.7	21.6	17.7	13.8	9.9	5.7
25	26.0	19.4	14.9	11.3	8.2	5.4	3.0	1.1
30	17.5	11.8	8.2	5.6	3.5	1.9	.8	.2
35	11.7	7.2	4.5	2.7	1.4	.6	.2	.01
40	7.6	4.2	2.4	1.2	.6	.2	.04	.00
45	5.0	2.5	1.2	.6	.2	.06	.01	.00
50	3.2	1.4	.6	.3	.08	.02	.00	.00

Figure 3. Rates of area cutting in fireline construction can be converted into chains per man per hour for a variety of line widths.


5
4
3
2
1
0
Chains/man/hour
1 foot
2 feet
3 feet
4 feet
5 feet
6 feet
8 feet
10 feet
0
10
20
30
40
50
Square yards/man/hour

DISCUSSION

The highly organized California Department of Corrections and U. S. Forest Service "hot shot" crews are called in on fires that have gone beyond the initial attack phase. These large crews are often used, but their work is considered different from the usual initial attack operations. The work rates of these large crews are important to planning, but more relevant to actual fires requiring operational estimates to meet a given situation.

Expression of work rates in square yards standardized rate measures for the various fuel types. Uniformity of the area construction rates is apparent by comparison of the rates of the four fuel groups shown in Table 1. The area rate analysis emphasizes the point that linear rates are partially a function of the greater fireline width required in heavier fuels. The measure of the resistance to control is strongly influenced by the widths needed to provide an adequate fire break.

A comparison with earlier published rates shows that in lighter fuels (Group I), the new rates, found in this study, are much lower. In Group I, for example, line construction will average above 4.4 chains during the first hour, according to the earlier rates. This rate is based on an expected average line width of 2.5 feet. A comparable figure for Group I in this study is a rate of nearly 22 square yards per hour (Table 1). If we convert the area rate to chains with an average width of 2 feet, the linear rate is about 1.5 chains per man; and if the width is about 3 feet, the rate is 1 chain. A similar comparison made in the most resistant fuels (Group IV) shows an average published hourly rate of 0.4 chain and an average width of 6 feet. The present study shows an area rate at 1

hour of 12.4 square yards, with an average width of 5.8 feet, or a linear rate of about .29 chains per man per hour. These differences in the basic rate for the less resistant fuels can affect crew assignments.

Expressing the area or linear work rates as a probability of reaching a specific work-rate permits the fire boss to adjust his crew allocations according to his assessment of the situation. His view of the probability of completing a given work assignment in a specified amount of time will be influenced by his evaluation of such factors as: (a) the importance of a particular segment of line to the fire control, (b) expected fire behavior, (c) difficulty of the terrain, and (d) knowledge of the crew given the job.

CONCLUSIONS

Some conclusions from this analysis of the data may be summarized as follows:

1. After 8 hours, only about one-half of each additional hour is spent on actual line construction.
2. Area units of work rates are roughly equal in the four fuel groups considered. This is an indication that resistance to control is a function of required line width.
3. Previously used rates of chains per man in light fuels are three to four times faster than rates computed in the same fuels in this study.
4. Measured line width in this study was about 1.5 feet wider than the width considered normal for the light fuel (Groups I and II).
5. Studies of this type for local fuels and crews could be made by administrative units by following the procedures described and using available computer programs.

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